

# A DAMAGE MODEL FOR MASONRY INFILLED FRAMES

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## Abstract

The effect of infill walls on the behaviour of frames is widely recognized, and, for several decades now, has been the subject of numerous experimental investigations. However, the analytical modeling of infilled panels and frames under in-plane loading is difficult and generally unreliable. From the point of view of the simulation technique the models may be divided into micromodels and simplified (or macro-) models. Based on the equivalent strut approach (simplified model), in this paper a damage model is proposed for the characterization of masonry walls submitted to lateral cyclic loads. The model, developed along the lines of the Continuum Damage Mechanics, have the advantages of including explicitly the coupling between damage and mechanical behaviour and so is consistent with the definition of damage as a phenomenon with mechanical consequences.

## 1 Introduction

Masonry infill panels have been used in reinforced concrete frames structures as partition walls. However, because of the complexity of the problem their interaction with the bounding frame is often neglected in the nonlinear analysis of building structures. Such an assumption may lead to an important inaccuracy in predicting the response of a structure specially when subjected to strong lateral loads, such as earthquakes. In fact, in these cases, the effect of infill walls is widely recognized on the behavior of frames and has been the subject of numerous investigations in the last decades. An extensive review of research on infill frames have been reported by Calvi [1].

Analytical modeling of nonlinear behaviour of masonry elements under in-plane loading is relatively difficult and generally unreliable since the masonry is an nonhomogeneous and anisotropic material with no elastic behaviour even for small deformations. Different models have been proposed to represent lateral load-displacement relationships. As it is well known, from the point of view of the simulation technique the models may be divided into micromodel and simplified (or macro-) models.

The first class, based essentially on the Finite Element Method requires the formulation of the constitutive equations of the materials of the infill through the modeling of the masonry blocks and mortar joints as discrete elements with links between them. From the first approach developed by Mallick and Severn [2] using the finite element method for the

analysis of 2D infilled frames, different alternative have been proposed using a micromodel. Among these, we could mention Liauw and Kwan [3], Papia [4], El Haddad [5], May and Naji [6] or, more recently, Lotfi and Shing [7], Mehrabi and Shing [8] or Sing *et al* [9]. However these models are too complex to be used for practical modeling of the nonlinear hysteretic behavior of masonry walls.

Because of it, the second class, simplified models, plays an important rule enabling the representation of the behaviour of an infill panel as a whole since a single (or few) diagonal strut element simulates each infill panel, identified as a structural member with its own behaviour. Besides the obvious advantages in terms of computational simplicity, the main advantage of macro modeling is using integral mechanical properties obtained from testing masonry panels which is very interesting from an engineering point of view since the masonry itself is a very heterogeneous material and the distribution of material properties of constituent elements is practically unpredictable.

Holmes [10] was the first in proposing replacing the infill by an equivalent pin-jointed diagonal strut of the same material assuming that its width was the third part of the diagonal between the two compressed corners. Stafford Smith and Carter [11] proposed a theoretical relation for the width of the diagonal strut based on the relative stiffness of infill and frame. An alternative proposal was given by Mainstone [12]. The first model simulating the infill behavior with non-linear diagonal struts was proposed by Klingner and Bertero [13]. Most recent approaches have been proposed by Chrysotomou *et al* [14] and Zarnic [15].

Essentially, progress of these models consisted of the introduction of an increasing number of characteristics into the strut element in order to simulate the behavior of the infill panel.

Based on the equivalent strut approach, in this paper a damage model is proposed for the characterization of masonry walls submitted to lateral cyclic loads. Obviously, the characterization of the structural damage is a subjective matter so the main problem is its quantification. Here, the strut element is modelled as a simple longitudinal inelastic spring simulating equivalent bracing acting directly between the two compressed corners of the frame and its behaviour law is formulated using the concepts and principles of the Continuum Damage Mechanics. For it, the axial force vs. deflection relation is formulated through the effective stress concept and the strain equivalence principle. Using this approach, a scalar damage variable appears in the constitutive equations for characterizing isotropic damage processes.

These models, developed along the lines of the Continuum Damage Mechanics, have the advantages of including explicitly the coupling between damage and mechanical behaviour and so are consistent with the definition of damage as a phenomenon with mechanical consequences. To define them completely, it is necessary to fix the evolution laws of the plastic strain and damage variables using dissipative potentials.

The strut element resultant is used for simulation of inelastic response of masonry infilled reinforced-concrete frames. The same kind of element is used for modelling the frame beam and the column. It consists of three successively connected components, flexural springs at the ends of each element and an axial spring. The constitutive equations for the flexural effects are formulated as a generalization of the concepts used in lumped plasticity models in order to include also the dissipative effects produced by structural damage. According to this frame model, damage effects are assumed to be concentrated at the ends of the member. This formulation can be considered as simplified damage mechanics for frames. The corresponding constitutive equations for the elastoplastic damage model resultant are formulated, like in the case of infilled walls, incorporating the concepts of the Continuum Damage Mechanics to the simplified models. More details about the model used for frame members can be found in Flores *et al* [16] and Perera *et al* [17].

The non-linear strut element, developed for simulation of infill walls and the flexural element with non-linear hinges for simulation of frame members are added into a existing software for non-linear analysis of structures. The computed prediction of masonry infilled frame behaviour is compared with the response of dynamically tested specimens. From the results some conclusions are obtained about the suitability of the proposed model.

## 2 Analytical modeling of masonry infill panel for monotonic response

The model developed here is based on a simplified or global approach. This development assumes that the global effect of the infill panel on the response of the structure can be modeled replacing the panel by a diagonal masonry compression strut, or, for cyclic loading, using a bi-diagonal system of struts (Figure 1). Since the tensile strength of masonry is negligible, the struts are considered to be ineffective in tension and, then, each strut is activated only in compression. This approach appears to be very attractive due to the obvious advantages in terms of computation simplicity and efficiency since the combination of both diagonal struts provides a lateral resisting mechanism able to represent the effect reached when load is applied in opposite directions. Strut element is modeled as a simple longitudinal inelastic spring loaded axially. The behavior of the spring is described in terms of the axial force-axial deformation relation of the strut (Figure 2). This relation is developed here using the concepts of the Continuum Damage Mechanics and, therefore, on thermodynamics of irreversible processes. Then, using the effective stress concept and the strain equivalence principle [18], the following relation is obtained:

$$N = K_0(1-d)\delta^e = K_0(1-d)(\delta - \delta^p) \quad (1)$$

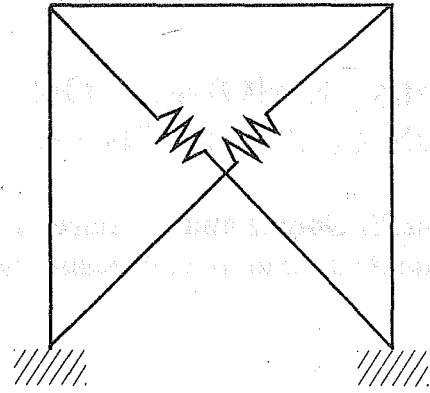


Figure 1: Strut model



Figure 2: Axial spring

where  $N$  is the axial force of the strut,  $\delta$ ,  $\delta^e$  and  $\delta^p$  are the total, elastic and plastic elongations of the strut, respectively,  $K_0$  is the initial stiffness to cracking and  $d$  is the internal damage variable representing the degradation of the infill.

As it can be observed from Equation (1) the strut behavior is controlled through the evolution of the plastic elongation and the damage variable. In fact, the damage index,  $d$ , can be considered as a measure of the progressive decrease of the effective width of the diagonal compression strut, due to the cracking occurring in the infill panel by tension effects.

In order to characterize completely this model, it is necessary

to specify expressions for  $K_0$ ,  $d$  and  $\delta^p$  in Equation (1).

Many alternative approaches have been proposed in the literature to estimate the initial stiffness  $K_0$ . The underlying concept employed to calculate this parameter is based on the approach used to determine the equivalent strut width. Mainstone [12] proposed an effective width of the diagonal compression strut as a function of infill to frame stiffness ratio. This relative stiffness plays a key role to the estimation of the panel's behavior and, therefore, in predicting its stiffness. Klingner and Bertero [13] or, more recently, Dawe and Seah [19] are based on Mainstone's formulation.

The estimation of the evolution laws for damage  $d$  and plastic elongation  $\delta^p$  are derived within the framework of thermodynamics of irreversible processes and their treatment is the purpose of the next subsection.

### 2.1 Evolution laws

The evolution of plastic and damage variables requires the formulation of the dissipative potentials. Then, the choice of the dissipative potentials is a critical point in this theory.

As plastic potential, assuming positive values for compressive forces and shortenings the following expression shown in Figure 3, is proposed:

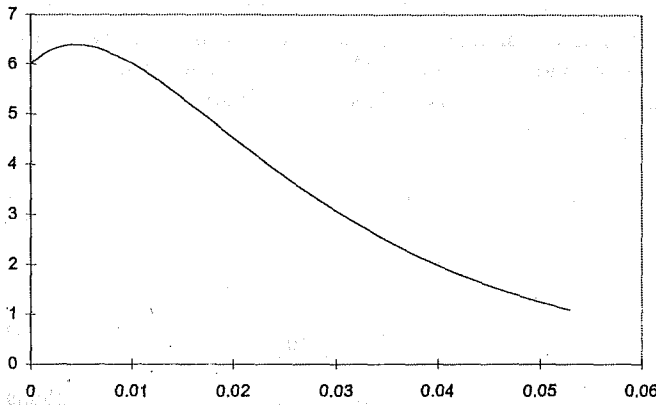


Figure 3: Plastic potential

$$f = N - \left[ A_1 e^{-B_1 \delta^P} + A_2 e^{-B_2 \delta^P} \right] \quad (2)$$

being  $A_1$ ,  $B_1$ ,  $A_2$  and  $B_2$  four constants of unknown value whose value has to be obtained in order to define completely the potential. For it, it is assumed that in a monotonic loading the following conditions apply (Figure 3):

$$\begin{aligned} \frac{dN}{d\delta^P} &= K_0 \Rightarrow \delta^P = 0 \quad \text{and} \quad f = 0 \\ N &= N_y \Rightarrow \delta^P = 0 \quad \text{and} \quad f = 0 \\ \frac{dN}{d\delta^P} &= 0 \Rightarrow \delta^P = \delta_u^P \quad \text{and} \quad f = 0 \\ N &= N_u \Rightarrow \delta^P = \delta_u^P \quad \text{and} \quad f = 0 \end{aligned} \quad (3)$$

where  $N_y$  is the yielding axial force,  $N_u$  the ultimate axial force and  $\delta_u^P$  the plastic elongation that corresponds to the ultimate axial force.

Equation (2) is very similar to the one proposed in [20], obtained through experimental studies.

The four parameters,  $K_0$ ,  $N_y$ ,  $N_u$  and  $\delta_u^P$  could be identified by using empirical prediction formulas calibrated to experimental tests. However this is not very easy since in most of cases we lack of information related to the properties of the materials used for the infills.

Many alternative approaches have been proposed in the literature such as it was commented referring to the initial stiffness,  $K_0$ , in the previous subsection. Concretely for the strength parameters  $N_y$  and  $N_u$ , Dawe and Seah [19] presented suitable expressions.

The ultimate plastic elongation can be estimated through the ultimate total elongation, regarding the conclusions of different experimental tests. Zarnic and Tomasevic [21] made an study about the seismic behavior of reinforced concrete frames infilled with masonry. In these tests, cracking began when lateral displacement reached a value of about 0.2%. More studies about it can be found in Pires and Carvalho [22], Manos *et al* [23] and Zarnic [24].

Related to the damage evolution law, in the model it is assumed that damage is associated to some plastic strain. Then, the yielding axial force agrees with the cracking force. To define damage an energy concept has been employed and the following expression is proposed

$$d = \frac{E(\delta^P)}{E_\infty} \quad (4)$$

being

$$E(\delta^P) = \int_0^{\delta^P} N(\delta^P) d\delta^P \quad (5)$$

the energy dissipated by the element and

$$E_\infty = \int_0^\infty N(\delta^P) d\delta^P \quad (6)$$

the value of the maximum dissipated energy which corresponds to the fracture. Due to the difficulty of determining  $E_\infty$ , a theoretical value has been obtained from  $E(\delta^P)$  when  $\delta^P \rightarrow \infty$ .

From Equations (2), (4), (5) and (6), operating, the following expression results for damage:

$$d = - \frac{A_1 B_2 e^{-B_1 \delta^P} + A_2 B_1 e^{-B_2 \delta^P}}{A_1 B_2 + A_2 B_1} + 1 \quad (7)$$

where it can be observed that it is associated to plastic deformation.

The graphical representation of Equation (7) is shown in Figure 4.

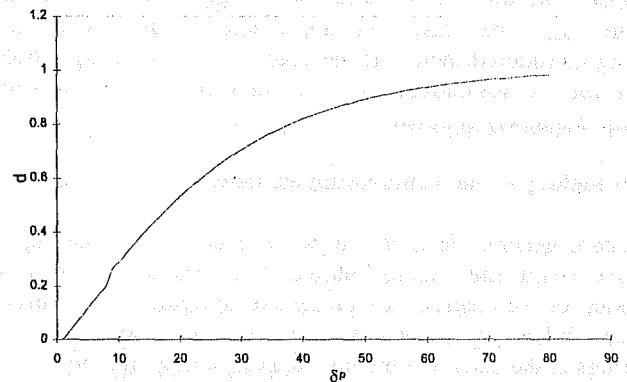


Figure 4: Graphical representation of Equation (7)

### 3 Hysteretic model

Following the development of the first model (monotonic response), a global model has been proposed for the infill panel for simulating the response when subjected to repeated loading reversals.

For it, a pair of bidiagonal struts is employed, each connected to two opposite corners of the frame. Each strut is activated only in compression and for positive deformations.

The phenomena reproduced by the model are the stiffness degradation due to cracking, the development of plastic strain

and the pinching. All these phenomena are controlled through the damage and plastic strain variables.

As it was seen in the last section, the monotonic curve is defined in terms of plastic strains. When cracking force is reached, a gradual spreading of cracking produces a stiffness degradation which is controlled by the damage variable,  $d$ . Pinching of hysteresis loops due to opening and closing of masonry cracks is a commonly observed phenomenon in masonry structural systems subjected to cyclic loading. Unloading and reloading rules for hysteretic loading allow the reproduction of the sliding and pinching effects. Unloading is performed elastically, considering the stiffness  $K_o(1-d)$ , to a zero stress:

$$N(\delta^p) = 0 \quad (8)$$

then, sliding occurs

In going from tension to compression, cracks are not considered closed up to reach a sliding displacement,  $\delta_{des}$ , defined between the cracking displacement,  $\delta_{cr}$ , and the maximum plastic displacement reached previously,  $\delta_{max}^p$ . This sliding displacement is defined as [25]:

$$\delta_{des} = \begin{cases} 0 & \delta_{max}^p < \delta_{cr} \\ \beta\delta_{cr} + (1-\beta)\delta_{max}^p & \delta_{max}^p > \delta_{cr} \end{cases} \quad (9)$$

being  $\beta$  a parameter of the model and  $\delta_{cr} = (N_{cr} / K_o)$ .

When  $\delta_{des}$  is reached, cracks begin to close progressively adopting for it the following constitutive equation:

$$N = \left[ A_1 e^{-B_1 \delta_{max}^p} + A_2 e^{-B_2 \delta_{max}^p} \right] \frac{\delta - \delta_{des}}{\delta_{max} - \delta_{des}} \quad (10)$$

Being  $\delta_{max}$  the maximum displacement reached in previous stages. The limit of this stage is a displacement  $\delta$  with the value  $\delta_{max}$ . From this point the monotonic curve is reached being considered then that the cracks are completely closed and the corresponding stiffness defined in the previous section is newly adopted.

#### 4 Modeling of the beam/column element

A more general element can be used both for modeling of frame beam and frame column. The assumed mechanical model for the element is represented in Figure 5. It consists of the following successively connected components: flexural springs at the ends of element, an axial spring and the central elastic member. In this way, dissipative deformations (plastic and damage deformations) are lumped at its two ends. This model, adding the damage effect, is consistent with the traditional assumptions of plastic hinge (plastic rotation) and bar hinge (axial deformation).



Figure 5: Mechanical model for the beam/column element

The strength-deformation relation of flexural springs is expressed as moment vs. rotation taking into account the effect of flexural damage. The damage effects are included in the constitutive law using the notions and principles of Continuum Damage Mechanics through the effective stress concept and the strain equivalence principle such as it was displayed in the last section. The following relations are obtained:

$$\theta_i^d = \frac{d_i}{1-d_i} \frac{L}{4EI} M_i \quad (11)$$

$$\theta_j^d = \frac{d_j}{1-d_j} \frac{L}{4EI} M_j \quad (12)$$

being  $d_i$  and  $d_j$  damage variables due to flexural effects associated at each end of the member.

Plastic and damage potentials associated to the beam/column elements are defined such as they are displayed in [17]. These potentials are completely defined through the obtention of the corresponding values of the parameters appearing into them. For it, significant limit states of the reinforced concrete cross-section are employed.

In particular, we employ the cracking moment ( $M_{cr}$ ), yielding ( $M_y$ ) and ultimate moment ( $M_u$ ) and the ultimate plastic rotation ( $\theta_u^p$ ). The moment vs. curvature relations can be calculated by one of the known procedures. Then the following conditions apply for monotonic loading:

$$\begin{aligned} M = M_{cr} &\Rightarrow d = 0 \\ M = M_p &\Rightarrow \chi^p = 0 \\ M = M_u &\Rightarrow \theta^p = \theta_u^p = \chi_u^p l_p \end{aligned} \quad (13)$$

being  $\chi_u^p$  the ultimate plastic curvature and  $l_p$  the equivalent plastic hinge length.

It is clear that the cross-section properties  $M_{cr}$ ,  $M_p$ ,  $M_u$  and  $\chi_u^p$ , consequently, the parameters are dependent of the axial force  $N$  developed at the member. Therefore, the parameter values have to be obtained for any axial force  $N$  through the numerical resolution of Equations (13).

More details about the modeling of the beam-column element can be found in Perera *et al* [17].

#### 5 Results

The proposed model was validated by comparison with experimental tests performed on masonry infilled frames.

For it, one-bay reinforced concrete frames with masonry panels were taken as a measure of comparison. These frames were tested at the LNEC in Lisbon under horizontal cyclic loading. The model had a height of 1.80 m. and a length of 2.40 m.. The columns and the beams had respectively 150 mm by 150 mm and 200 mm by 150 mm sections.

To obtain a better evaluation about the performance of the model, the necessary parameters were taken from the numerical results obtained using a finite element model for monotonic loading. Comparison between numerical results obtained with the proposed model and with a finite element model [25,26] are shown in Figures 6 and 7, respectively.

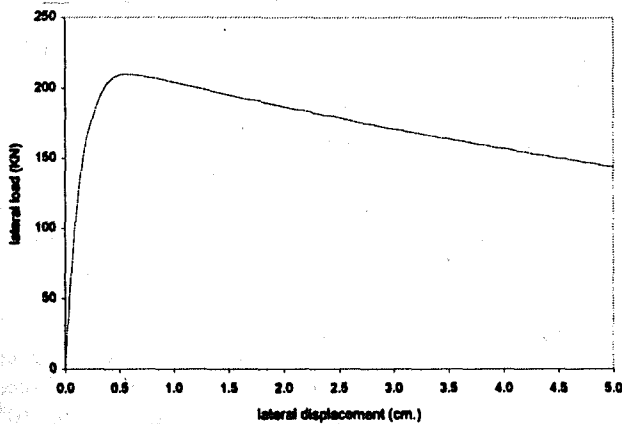


Figure 6: Numerical results for monotonic loading (macromodel)

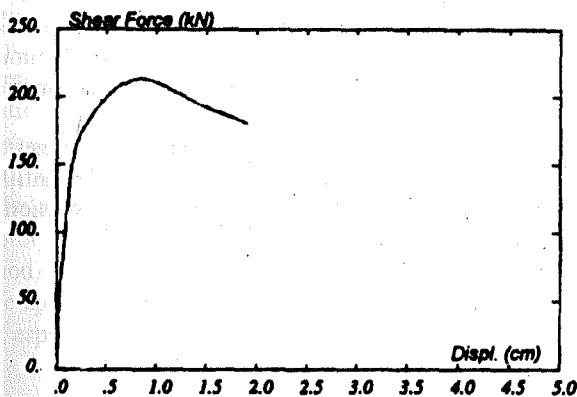


Figure 7: Numerical results for monotonic loading (micromodel)

For the study of the hysteretic response, displacement steps of increasing amplitude were applied horizontally. Comparing the experimental results [25,26] in Figure 8 with the numerical ones (Figure 9), it appears to be very clear that proposed model is successful to simulate the global response of the structural element.

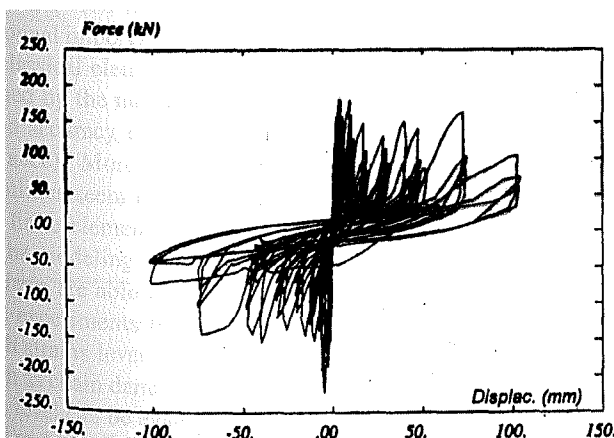


Figure 8: Hysteretic response (Experimental)

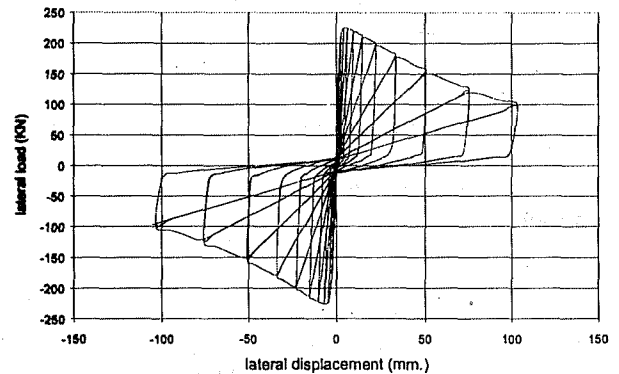


Figure 9: Hysteretic response (macromodel)

## 6. Conclusions

An equivalent-strut model based on the Continuum Damage Mechanics has been proposed. The results appear to be good and, therefore, the model seems to be suitable for practical use and further developments.

Future investigations could be orientated to the additional validation of the proposed model by means of tests of multi-storey, multi-bay frames.

In the same way, some phenomena not considered by the model, such as strength deterioration could be added.

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